

Review

Grapevine quality: A multiple choice issue

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ABSTRACT

Over decades, the concept of grape quality has evolved emphasizing its multidisciplinary nature and that the same “desired quality” might correspond to even strikingly different compositional patterns. The review takes a long journey throughout the multiple factors impinging on grape quality, not excluding also sections devoted to table grapes. It starts with a thorough survey on the genetic factors influencing grape quality focusing on diversity in different compositional traits (sugar, organic acid, pH, phenolics and aromas) relating to cultivars and clones. Then, most recent knowledge about the effects of soil characteristics, nutrients, light, temperature and water availability, as standalone factors or in interaction, on grape quality are summarized. The more applied section of the review introduces the very much debated yield-quality relationship that, over years, is being interpreted with more flexibility and with greater consensus for an “optimal yield range” that within a given context can anyway reach the desired quality. The impact of the main summer pruning operations (leaf removal, shoot and cluster thinning, shoot trimming) is reviewed and special care taken to highlight most recent contributions with adjusted summer pruning developed to either adapt to climate change issues or to induce specific composition patterns. Review ends with a quick survey on methods nowadays available for fast, non-destructive grape composition assessment.

1. Introduction

Finding a shared definition of “quality” for wine grapes is still a formidable task simply because quality, being dependent upon individual wine taste, stylistic preferences, vintage variation and a number of other factors, is tremendously subjective. Based on a given final wine target, grape “quality” often reflects quite different “optimal maturity or ripening patterns” and “quality” can exist in every category of wine, from box and jug wines to the very expensive and exclusive premium wines.

Thus, optimal grape maturity would correspond to a strikingly different grape composition depending upon the wine styles (e.g. fresh white sparkling vs. aged reds) and its identification in time is the crucial decision. Total soluble solids (TSS) concentration is still the most used parameter to assess ripening and, in several cases, to tag grape prices. The validity of sugar level as an estimator of berry function is not under

debate and recent findings have shown that, in cultivars such as Merlot (Bondada et al., 2017) and Chardonnay (Tillbrook and Tyerman, 2008) a level of 24–25 °Bx likely sets the threshold beyond which a further TSS increase is primarily due to berry dehydration or deterioration. Such threshold is indeed cultivar dependent though; in Shiraz berries attained maximum mass at about 20 °Bx and then started to shrink; conversely, cv. Muscat Gordo Blanco showed no phloem impedance until 27 °Bx (Coombe and McCarthy, 2000). Unfortunately, a TSS-derived good “maturity level” does not necessarily correspond to the best overall maturity and in some years the grapes will be ripe and have a distinct varietal character at 20 °Bx while another year they may still not have a ripe varietal character at 23 °Bx (Barnuud et al., 2014). The decoupling between technological maturity parameters (i.e. sugar, acids or their ratio), phenolic maturity (i.e. quantity and quality of all tannins and pigments) and aromatic ripeness (i.e. typical olfactory features reached without appearance of untypical ageing or excessive

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veggie-green aromas) is considered to be aggravated under a global warming scenario (Pallioti et al., 2014). In warm districts, it is quite common to face excessively fast sugaring while anthocyanins and flavors accumulation is still lagging behind. In more general terms, wine grape quality attributes in white cultivars should aim at the confluence between the desired sugar-to-acid ratio coupled with moderate must pH and clean varietal character; in reds non limiting sugar and anthocyanin pools have to merge with ideal texture of the grape tannins in the skin and the seeds.

Quality of table grape includes intrinsic (i.e. visual, mechanical, chemical, etc.) and extrinsic (i.e. price, country of origin, cultivar, production method, etc.) attributes. The consumer's perception of intrinsic attributes can be defined as 'acceptability'. As a consequence, the perception of quality may change in the marketing chain and among the types of consumers in the different countries. Therefore, sensory evaluation is a valid approach to measure consumer preference and satisfaction (Ma et al., 2016).

Appearance is one of the major factors the consumer uses to evaluate the quality of table grape, especially visual attributes such as berry size, shape and color (Ferrara et al., 2017) together with taste, aroma and texture. Consumers like large, seedless berries along with pleasant flavour and aroma (Costenaro da Silva et al., 2010). Seedlessness is a key factor for quality (Vargas et al., 2013) and young consumers prefer seedless varieties because the absence of the seeds makes the berry easier to chew, thus avoiding the astringency of the seeds or the spitting. Color (from pale green to nearly black) is a direct sensory characteristic making table grape more or less attractive. In addition to visual characteristics, physicochemical properties are involved in quality evaluation (Crisosto and Crisosto, 2002; Jayasena and Cameron, 2008). Texture of table grape berry includes several attributes such as hardness, elasticity, shape and sensations in the mouth during chewing (Rolle et al., 2012).

The sensory quality of table grapes depends primarily on TSS, TA, organic acid composition and the balance between these factors (Munoz-Robredo et al., 2011). TSS correlated to ripeness is one of the grape properties most likely to match consumer perceptions of berry quality and preference. Organic acids balance the mouth-feel sensation of quality of table grapes, but high acidity can negatively affect palatability. Table grapes are harvested after the berries reach minimum maturity requirements (TSS: TA \geq 20:1 if the Brix level is greater than or equal to 12.5 and less than 14 °Bx, TSS:TA \geq 18:1 if the Brix level is greater than or equal to 14 and less than 16 °Bx).

The aroma perceived during berry chewing is a quality factor of great importance as a result of the volatile composition of each cultivar (Ruiz-García et al., 2014). Muscat aroma is greatly appreciated in grapes destined for fresh consumption and is directly related to monoterpenes, such as linalool, rose oxide, citral, geraniol, nerol and citronellol (Fenoll et al., 2009).

Table grapes are a major source of health promoting bioactive compounds (Baiano and Terracone, 2012; Lutz et al., 2011). Colored grapes are the most active because of their richness in phenolic compounds with multiple biological effects and potential health benefits (Carrieri et al., 2013; Guerrero et al., 2009).

The quality of table grapes tends to deteriorate (either on vine or in storage) and this is one of the foremost problems faced by the stakeholders. It is well known that one of the major postharvest problems of table grape is its susceptibility to grey mold which can limit the shelf life during storage and retail marketing (Romanazzi et al., 2012). Fungal decay would affect appearance characteristics, firmness and weight loss of clusters during cold storage. Since sulfur dioxide fumigation used to preserve quality and extend shelf life of table grapes has negative effects on food safety and the environment, different products such as chitosan, salicylic acid, etc., can be used to reduce decay incidence and improve grape quality (TSS, phenolic compounds, sensory attributes) and shelf life (resistance to *Botrytis cinerea*) during cold storage (Shen and Yang, 2017). From a storage point of view, berry

shattering, decay and stem browning are some of the most important factors limiting the quality and marketability of table grapes (Cantín et al., 2007).

2. Genetic factors influencing grape quality

A large diversity of grape cultivars is used in the wine industry with distinct characteristics in berry traits, such as berry size, color, flavors, and aromas (Pelsy, 2010; This et al., 2006). Such a wide range of cultivars is largely a result of sexual crossing (natural or introduced by breeders) and natural mutation (This et al., 2006). In addition to cultivars, different clones of the same cultivar may also bring further diversity to grape quality (Pelsy, 2010). This diversity is important not only for providing different wines but also for furnishing opportunities to adapt to the future climate change conditions (Duchêne, 2016) and for enabling the identification of genes controlling quality traits in grapevine (Pelsy, 2010).

2.1. Diversity of sugars among cultivars and clones

Sugar composition and concentration vary with cultivars and clones in grape berry. In most wine grapes (*Vitis vinifera* cultivars), berry starts, at the onset of ripening, to accumulate roughly equal amounts of glucose and fructose, with very low levels of sucrose. However, *V. labrusca* and *Muscadinia rotundifolia* varieties and interspecific hybrids can also accumulate non-negligible amount of sucrose (Liu et al., 2006). Sugar concentration, measured as TSS, varies from 13.7–31.5 °Bx between different cultivars (Kliwer, 1965, Kliwer, 1967a; Kliwer, 1967b; Liu et al., 2006). Moreover, sugar content can vary as much as 23 g/L (~1.4% in potential alcohol) among 10 clones of Cabernet franc (Van Leeuwen et al., 2012), or 2.0–2.5 °Bx (~1.0–1.2% in potential alcohol) among 15 clones of Aglianico and 21 of Muscat of Alexandria (De Lorenzis et al., 2017). Almost 90% of table grape cultivars (*Vitis vinifera* and hybrids *V. labruscana* \times *V. vinifera*) are hexose accumulators, which means fructose, glucose, and trace amounts of sucrose (Shiraishi et al., 2010).

The sugar concentration at maturity is a result of various processes, including sugar supply from the leaves, loading via phloem, metabolism in cells, transport into vacuole for storage (Lecourieux et al., 2014), and water dilution effect (Dai et al., 2016; Sadras et al., 2008). The complex nature of the sugar concentration hampers the identification of its genetic markers. Several quantitative trait loci (QTLs) have been recently reported at ten linkage groups (LG1, 2, 3, 4, 7, 9, 11, 14, 17 and 18) (Chen et al., 2015), at LG2 (Houel et al., 2015), or at LG1 and LG6 (Yang et al., 2016) in different mapping progenies. These QTLs had minor effects and were not stable among growing conditions. Interestingly, Duchêne et al. (2012) showed that the variability in sugar concentration was strongly reduced after considering the differences in leaf-to-fruit ratio and dates of véraison within a progeny and argued that suitable pre-processing of the phenotypic data is necessary for detecting genetic markers that are involved in sugar metabolisms and/or transport. One option might be to couple sugar accumulation profile with eco-physiological models to dissect complex traits into more stable and environmental-independent processes, in order to facilitate genetic assisted breeding (Prudent et al., 2011).

2.2. Diversity of organic acids among cultivars and clones

Acidity is one of the main characteristics of wines, driving their sensory properties, chemical and microbiological stability as well as ageing potential. Grape acidity can be assessed by titratable acidity or pH. However, the pH better reflects the content of the grapes in organic acids, mainly malic and tartaric acids, and in cations, mainly potassium (K^+). Indeed, K^+ partly neutralizes organic acids: the higher the concentrations, the higher the pH. The genotypes used, both for scions and rootstock varieties, play a major role in the final acidity of wines, with

pH varying at harvest from 2.91 (Duchêne et al., 2014) to 4.36 (Kliewer et al., 1967) in *Vitis vinifera* grapes.

Phenology is the first source of genetic variations of grape acidity at harvest. Malic acid is degraded during ripening, whereas potassium accumulates. The longer and the warmer the ripening period, the lower will be the acidity at the end of the season. The large genetic variability of precocity of véraison is consequently a major source of variation of acidity at harvest. Nevertheless, genetic variability for the concentrations of tartaric and malic acids was assessed in germplasm collections. For *Vitis vinifera* varieties, concentrations for tartaric acid ([Tart]) at harvest between 21 mM and 63 mM and concentrations for malic acid ([Mal]) between 11 mM and 51 mM were reported (Kliewer et al., 1967). When including interspecific hybrids, the range of variations was larger: 10–61 mM for [Tart] and 3–53 mM for [Mal] (Liu et al., 2006). In both studies the acidity for table grapes was slightly lower than for wine grapes. In particular, in table grapes (*Vitis vinifera* and hybrids *V. labruscana* × *V. vinifera*) mean titratable acidity resulted 3.8 g/L, 3.7 g/L and 3.7 g/L in European, North American and Japanese cultivars, respectively (Shiraishi et al., 2010). The ratio tartaric acid to malic acid ranged from 0.78 (cv. Muscat of Alexandria) up to 1.99 (cv. Italia). When considering the whole genus *Vitis* concentrations reached 79 mM for [Tart] (*Vitis solonis*) and 203 mM for [Mal] (*Vitis berlandieri*) (Kliewer, 1967a). Tartaric acid is a stronger acid than malic acid (Ribéreau-Gayon et al., 2006) which means that for the same molar concentration, pH will be lower with tartaric acid because of a higher release of protons. Tartaric acid has more pleasant organoleptic properties than malic acid, is not metabolized during fermentation, but is also less sensitive to climatic conditions during ripening. Varieties with a high tartaric acid content are consequently better adapted to climate change. The range of [Tart]/[Mal] ratio, 0.64–3.41 in *V. vinifera* varieties (Kliewer et al., 1967) and 0.34–5.85 within the genus *Vitis* (Kliewer, 1967a), is a possible resource for genetic adaptation.

Genetic variations for berry pH were described in progenies from *V. vinifera* varieties (Bayo-Canha et al., 2012; Duchêne et al., 2014) but the links with variations in [Mal], [Tart] or [Mal]/[Tart] are not established yet, even though QTLs were detected for these traits (Chen et al., 2015; Houel et al., 2015; Yang et al., 2016). The missing element is likely $[K^+]$: segregations for $[K^+]$ in progenies were reported (Bayo-Canha et al., 2012; Houel et al., 2015) but the low heritability of this trait (Houel et al., 2015) certainly impeded QTL detection. $[K^+]$ in juices also depends on the rootstock used, which could induce variations of pH between 3.76 and 4.27 in 'Shiraz' grapes (Kodur et al., 2013). Genetic variations for $[K^+]$ in leaves in hybrids from a rootstocks cross (Gong et al., 2014) open the possibility of breeding rootstocks for K^+ accumulation in scions.

2.3. Diversity of anthocyanins among cultivars and clones

Anthocyanins are a group of flavonoids that give the wide color spectrum in grape berry. They are not only essential quality factors but also have health benefits for humans due to their strong antioxidant activities (He et al., 2010). Skin total anthocyanin concentration was reported to vary between 0.003–7.510 mg g⁻¹ in table, hybrid, and wine grape cultivars (Liang et al., 2008; Mattivi et al., 2006). Differences among clones of the same cultivars were also reported (De Lorenzis et al., 2017; Van Leeuwen et al., 2012). Anthocyanins, flavanols, flavonols are more abundant in wine grapes with respect to table grapes (Liang et al., 2008). A large diversity also exists in the anthocyanin compositions; for example, in most wine grapes tri-hydroxylated anthocyanins are the major component, while di-hydroxylated anthocyanins predominate in cvs. such as Nebbiolo; most grape cultivars contain both acylated and non-acylated anthocyanins, while Pinot noir only contains non-acylated anthocyanins (Mattivi et al., 2006). Malvidin-derivatives are the most abundant components, accounting for more than 68% of total anthocyanins in both wine and table grapes (Liang et al., 2008).

UDP-glucose:flavonoid 3-O-glucosyltransferase (UGT) is the key enzyme for anthocyanin biosynthesis (Boss et al., 1996). Its expression is mainly controlled by the transcriptional factors (TF) MYBA1 and MYBA2 genes (Kobayashi et al., 2004; Walker et al., 2007) and other TFs (as reviewed in Kuhn et al., 2014). Insertions, deletions, or nucleotide mutations in the MYBA genes can all bring about white grape berries (Kobayashi et al., 2004; Walker et al., 2007). Genetic analysis further confirmed the importance of the color locus at LG2, which contains a cluster of MYB genes (including MYBAs) and can explain 62% of the variation in total anthocyanin content (Fournier-Level et al., 2009). In particular, Pinot gris and Pinot blanc are shown as mutations of Pinot noir through chromosome replacement and deletion at the color locus (Pelsy et al., 2015). In addition, anthocyanins transporters are also involved in determining anthocyanin accumulation (Francisco et al., 2013; Gomez et al., 2009; Gomez et al., 2011).

The fine tuning of anthocyanin composition is less studied (Costantini et al., 2015). Anthocyanin methylation is conducted by anthocyanin O-methyltransferase (VvAOMT) (Huguency et al., 2009) and this gene together with MYBA1 can explain a large proportion of variations in methylation levels in grape progeny (Costantini et al., 2015; Fournier-Level et al., 2011). Hydroxylation is controlled by the relative expression of F3'H and F3'5'H (Bogs et al., 2006; Castellarin et al., 2006), and genetic analysis showed that MYBA1 also plays a role in determining hydroxylation pattern in a progeny (Azuma et al., 2015). Recent functional analysis showed that an anthocyanin acyltransferase (Vv3AT) can produce most acylated anthocyanins in grape skins and the dysfunction of Vv3AT due to mutation is responsible for the absence of acylated anthocyanins in Pinot noir (Rinaldo et al., 2015). Several QTLs have also been identified for acylation at LG3, 7, 8, 12, and 18, but can only explain 6–12% of phenotypic variations (Costantini et al., 2015).

2.4. Diversity of aroma profiles among cultivars and clones

Wine aroma is produced by a complex mix of volatile organic compounds that are responsible for the pleasant experience of drinking a glass of wine. These compounds have different detection thresholds and some of them can have a major importance despite their very low concentration (Darriet et al., 2012). Aromatic molecules in wine can be found directly in grape berries, e.g. terpenols, norisoprenoids, methoxy-pyrazines, but they also can originate from precursors that will be modified during wine making or wine ageing. Aromas, or their precursors, already present in grapes are described as primary wine aromas, whereas secondary wine aromas are produced during the wine making process (alcoholic and malolactic fermentations, oak barrel storage) and tertiary wine aromas during wine ageing. Allelic variations, i.e. variations on the genomic DNA sequence, can create differences in the biosynthesis of aromas, or of aroma precursors, both between varieties and clones (Duchêne et al., 2009a, 2009b).

Monoterpenols are 10-carbon molecules with floral scents found in high concentration in berries of cultivars such as Gewürztraminer and varieties of the Muscat family (Mateo and Jiménez, 2000). Concentrations of free and glycosylated linalool alone can exceed 2 mg kg⁻¹ in Muscat de Frontignan berries (Bureau et al., 2000). 1-deoxy-D-xylulose 5-phosphate (DXOP) is the precursor of geranyl diphosphate (GPP), the substrate used by terpene synthases VvTPS to produce monoterpenols such as geraniol, linalool or α -terpineol. In aromatic genotypes, a mutation of a single base in the gene coding for the 1-deoxy-D-xylulose 5-phosphate synthase (DXS) is sufficient to enable a higher synthesis of DOXP, and subsequently GPP, in aromatic cultivars (Duchêne et al., 2009a; Battilana et al., 2011). Cytochromes P450 can further increase the diversity of isoprenoids compounds found in grapes (Ilc et al., 2017).

Sesquiterpenes are 15-carbon molecules produced by VvTPS from farnesyl diphosphate (FPP). Rotundone, for example, is responsible for the green peppery aroma in Shiraz grape (up to 700 ng kg⁻¹) and wine

(up to 145 ng l^{-1}) (Siebert et al., 2008). Its precursor, α -guaiane, is a sesquiterpene synthesized by VvTPS24 (Drew et al., 2016), which is then oxidised by the cytochrome P450 CYP71BE5 in grape berries to form rotundone (Takase et al., 2016).

Norisoprenoids are C13 breakdown products of carotenoids. 1,1,6,6-trimethyl-1,2-dihydronaphthalene (TDN) is responsible for the “kerosene-like” aroma typically found in aged Riesling wines. Other norisoprenoids such as β -ionone or β -damascenone are less genotype-dependent.

Methoxy-pyrazines are nitrogen-containing heterocyclic molecules. They are found in different grape varieties up to 200 ng kg^{-1} . Their vegetable-like fragrance can participate to the character of Sauvignon blanc wines but is not appreciated when concentrations are too high (Guillaumie et al., 2013). 2-methoxy-3-isobutylpyrazine (IBMP) is an example of methoxy-pyrazine. Its non-volatile precursor, 2-hydroxy-3-isobutylpyrazine, is methoxylated by an S-adenosyl-methionine-dependent O-methyltransferase, VvOMT3, to form IBMP (Guillaumie et al., 2013).

Thiols are sulfur-containing molecules. 3-sulfanylhexasan-1-ol (3-SH) is an example of varietal thiol with a grapefruit-like aroma. Concentrations in wine can reach $19,000 \text{ ng l}^{-1}$ (Roland et al., 2011). 3-SH has been detected in Sauvignon blanc wines (Tominaga et al., 1998), but also in red wines such as Grenache (Ferreira et al., 2002). The potential precursors of 3-SH in grapes are cysteinylated and glutathionylated (Roland et al., 2011).

3. Environmental factors affecting grape quality

3.1. Soil characteristics

The impact that soil characteristics have on grape quality and wine styles unavoidably introduces the concept of “terroir” that, in short, can be defined as the way the vineyard environment shapes grape and wine quality. However, in broader and more appropriate terms “*terroir includes cultivar type, soil, climate, vineyard location, planting density, training system, pruning philosophy and the cultural and social milieu wherein the whole enterprise takes place*”. No doubt that soil with its physical and chemical features is a primary determinant of the “terroir”, yet the belief that the soil in a particular vineyard imparts distinctive compositional features to the grapes and the resulting wines is still strong in Europe, but less so in the New World viticulture (White, 2003). Two still challenging questions are: i) how important is “soil” within the terroir concept vs. for instance, climate and cultivar in determining grape quality and wine character? And ii) do we have convincing evidence of any causal relationships between soil and wine character? For the first question, a few studies in the past have either concentrated only on a single parameter of terroir being either climate (Gladstones, 1992; Huglin, 1978), soil (Seguin, 1986; Van Leeuwen, 2001) or cultivar (Riou, 1994) or when encompassing all three main factors (Rankine et al., 1971) the soils were situated in different climatic zones making it difficult to separate the effect of soils from that of climate. A study designed to overcome such inherent limitation where three red cultivars (Merlot, Cabernet franc and Cabernet sauvignon) grown on three soil types (gravelly, heavy clay, sand-clay) located in the Bordeaux region over five years (Van Leeuwen et al., 2004) showed that climate was overall more effective at determining grape quality than soil and cultivar and that soil type had significant effects on berry weight, sugar and total anthocyanins concentration. Though, the most striking result of this study was that the effects of soil on grape composition were largely brought back to soil influences on vine water status hypothesizing variation in water holding capacity, infiltration rates and accessibility to the water table. Conversely, mineral uptake from the vine or the ability of the soil to provide those nutrients did not appear to exert a significant influence on fruit quality. Overall, these results confirm earlier reports (Pomerol, 1989; Seguin, 1986) suggesting that a distinctive grape composition pattern and subsequent

wine characters has largely to be attributed to soil’s physical properties (e.g. texture, porosity, infiltration rates, rate of water supply to the roots, drainage), whereas the soil chemical properties are considered to be less influential provided that the nutrient supply is well balanced (no surpluses that promote excess vigor or toxicity and no serious deficiencies). Even in the absence of specific studies, literature provided several examples reinforcing the hypothesis that physical soil properties play a major role in grape quality. Gladstones (1992) argues that rocky and gravelly soils produce the best grapes and wines across a range of climates. As a matter of fact, the best Beaujolais wines are produced on shallow coarse-textured soils over granite and schist (Wilson, 1998). Here, the Gamay grape, a potentially vigorous cultivar is restrained in its growth and produce wines of elegant flavour. To add more, tasting made on wines produced within the three main soil types of St. Emilion and Pomerol (Bordeaux region) gave top scores to those coming from soils of type 1 and 3 (1: gravelly through the whole profile; 3: sandy to sandy-clay texture in the topsoil (30–50 cm deep)) becoming very high in silt and clay in the subsoil which quite often is also compact. Due to different reasons – in type 1 prevails fast infiltration into deep layer whereas in type 3 subsoil nature prevents roots to colonise deeper layers – both soil types induce a gradual water stress that, becoming significant post-veraison, helps at halting vegetative growth leading to higher fruit sugar concentration, lower malic acid and more concentrated anthocyanins and polyphenols at harvest. According to Lambert and Kashiwagi (1978) best soils for grape quality in Napa Valley are the benches in the foot slope regions where the soils are shallower, very stony, well drained and less fertile than the alluvial valley floor, whose soils often confer excessive vigor to the vine. To complete an array of examples, the case of the well-known “terra rossa” soils in Coonawarra (Australia) is emblematic; a 1 m deep light brown calcareous soil enriched with residual ferric oxide impurities from the weathering limestone and loess surmounts a deep subsoil layer of porous and fractured limestone. Such sequence allows good drainage during winter and good regulation of water supply during summer leading to better vine balance and optimal maturity (Halliday, 1993).

Tracking back to the second question posed at the beginning of this subchapter, it seems therefore unlikely that chemical soil features have a direct impact on grape quality and wine character. Too, demonstrating such direct relationship is also methodologically very tough since grape samples should be referred to a homogeneous soil type. Due to very high soil heterogeneity, this can be possible only when very small surfaces are considered (likely less than half an hectare). With increasing vineyard surface, the character of a wine is less and less likely to show a distinctive and defining influence of the soil. Soil variation, in combination with a variation in meso-climate, will mask a clear expression of the underlying terroir. Searching for a direct causal relationship between soil, grape quality and wine character was the objective of a long term study (1977–1998) carried out on cvs. Muller-Thurgau and Silvaner grown in large 1-m deep containers filled with soils from 7 different parent materials (Wahl, 2000). Cleverly, to eliminate the climatic variable from terroir, the containers were placed in a typical vineyard in the Franken region of Germany, with the aim of isolating the soil effect. Grape quality and wines from the trial were compared with wines made from the same varieties in the original locations whence the soils were located. Nevertheless, the effect of soil quality on grape composition and sensorial traits of the wines was very limited. Albeit shyly, though, literature reports some claims that traits conferred from parent rock material can be in some ways carried in grapes and wines. For instance, Wilson (1998) suggests that variation in the metal content (e.g. manganese) of the granite and schist accounts for the character of some Cru Beaujolais wines, whereas Darlington (1999) refers that particular minerals derived from the basalt enriching the Jory soil prevailing in the Willamette Valley in Oregon confer special character to the resulting wines. These last examples lead to the extremely fashioned concept of “minerality” of wines, defined as “the perception of the rocks in the soil, by the palate”. Someone can detect

chalk and flint in Chablis wines or slate in Mosel Riesling. Such relationship is quite tough to be scientifically demonstrated since rocks do not dissolve and then get taken up by the berries and then the wine. Besides, rocks do not have any specific taste. In more general terms, investigations aiming at establishing causal relationship between soil type and grape and wine quality will indeed benefit from approaches based on precision viticulture (Gatti et al., 2017) furnishing possibility to identify, even in small sized vineyard, areas of different vigor which, in a vast majority of cases, depend upon different physical and chemical characteristics of the soil.

3.2. Nutrient supply

3.2.1. Nitrogen

While it is quite well established that suitable leaf blade N concentrations at veraison should fall within 1.8–2.3% DM (Keller, 2015), the impact of nitrogen on grape composition and grape quality is often the combination of its direct effect on vine metabolism and indirect effects linked to its strong influence on vigor and yield. Excessive vigor increases the leaf area/yield ratio and reduces light penetration through the canopy. Ripening delay, reduction of TSS and increase of titratable acidity are effects generally associated to high level of N fertilization (Baiano et al., 2011; Delgado et al., 2004; Thomidis et al., 2016). Furthermore, canopy microclimate alteration (i.e. excessive shading associated with poor ventilation), in combination with increased bunch compactness, greatly enhances grape susceptibility to pathogens such as *Botrytis cinerea* (Thomidis et al., 2016); however, N fertilization also increases the thickness of berry epicuticular wax as well as the concentration of biochemical defense compounds (Mundy, 2008). Wine anthocyanin concentration is usually reduced under high N availability (Brunetto et al., 2009; Hilbert et al., 2003; Pérez-Álvarez et al., 2013) partly because of the increased flesh-to-skin ratio causing a dilution of anthocyanins and other compounds located in the skin (Keller et al., 1999). In particular, Soubeyrand et al. (2014) indicated delphinidin and petunidin as the compounds most negatively affected by N fertilization. In fact, N availability exerts a coordinated regulation of the flavonoid pathway in grapevine. In more details, genes encoding phenylalanine ammonia-lyase (PAL), chalcone synthase (CHS), flavonoid-3',5'-hydroxylase (F3'5'H), dihydroflavonol-4-reductase (DFR), leucoanthocyanidin dioxygenase (LDOX) exhibited higher transcript levels in berries from plant cultivated without nitrogen compared to the ones cultivated with 120 kg ha⁻¹ nitrogen fertilization (Soubeyrand et al., 2014). On the other hand, several papers have reported that moderate N application, in particular foliar application right after harvest, increased anthocyanin and flavonoids in berries and wines (Delgado et al., 2004; Portu et al., 2015a, 2015b; Portu et al., 2017). Conversely, N deficiency might exert negative effects on anthocyanin concentration, berry N, S-Cysteine conjugate precursors, TSS and titratable acidity (Des Gachons et al., 2005; Jreij et al., 2009).

Regarding volatile compounds, vineyard N fertilization was reported to positively affect concentration of some free and bound monoterpenes in the aged wines, depending on the compound and the vintage (Webster et al., 1993). More recent work emphasized the role of foliar N application in combination with sulfur at enhancing aromatic expression in Sauvignon blanc (Lacroux et al., 2008). In particular, in Sauvignon blanc juice, N application increases cysteine precursor levels, suggesting a positive effect on grape aromatic potential (Choné et al., 2006).

N application has a direct effect on yeast-assimilable nitrogen (YAN) content that may have a major impact on fermentation dynamic and wine properties. Low must YAN leads to low yeast populations and sub-optimal fermentation with increased production of undesirable thiols (e.g. hydrogen sulfide) and higher alcohol, and low production of esters and long chain volatile fatty acids. High must YAN leads to increased yeast biomass and higher maximum heat output due to greater fermentation strength, and increases formation of ethyl acetate, acetic acid

and volatile acidity (Bell and Henschke, 2005).

Finally, N fertilization timing is crucial for a better tuning of N supply vs. demand in the grapevine; N application at bloom and after harvest have been indicated as optimal techniques to limit vegetative growth and to increase yield, respectively (Neilsen et al., 2010)

3.2.2. Potassium

About 50% of K absorbed by grapevines is accumulated in the berry where it is mainly concentrated in the skin (Brunetto et al., 2015). K increase in berry is particularly high after veraison due to K redistribution from leaves (Blouin and Cruege, 2003). During this stage K plays an important role in the accumulation of sugars (Conde et al., 2007). Noteworthy, competition between K and sugar accumulation can occur due to their high osmotic potential; although there is a significant positive relationship between K content and sugar accumulation, there is a wide variability depending on the absolute concentration of K and sugars in berries (Mpelasoka et al., 2003). Poni et al. (2003) have reported that leaf blade K concentrations lower than 0.5% DM begins to significantly limit leaf assimilation rates. Although potassium is involved in a number of critical processes (enzyme activation, sugar synthesis, and osmoregulation), potassium excess in the berry has a strong negative impact on grape quality: it causes must pH increase, insolubility of tartaric acid with the formation of potassium bitartrate and the worsening of wine character and stability as well as alteration of wine color (Conde et al., 2007).

3.2.3. Phosphorous

Although P is involved in a number of physiological processes such as cell membrane formation, carbohydrate metabolism, protein synthesis, energy storage and transfer, there is poor information on the impact of P on grape quality; among few experiments available, Topalović et al. (2011) reported negligible effect on grape quality of fertilization with P in combination with other elements. Similar results were obtained by Schreiner et al. (2013) who reported a lower P concentration in Pinot noir must with no effect on grape yield in vines that did not receive any P fertilization. However, phosphorous deficiency can occur in acid soils with very low pH particularly where iron and aluminum content are high; strong P deficiency condition causes poor vegetative growth and fruit set as well as increased shot berry formation in the mid part of the rachis (Cook et al., 1983). Leaf blade P concentration below 0.14% resulted as limiting for vine yield and grape composition in Chenin Blanc even though it has been reported large genotypic variability regarding vine susceptibility to P deficiency (Skinner et al., 1988).

3.3. Light

The effects that amount and quality of solar radiation exert on berry ripening are quite difficult to be interpreted for two main reasons: i) observed effects on grape quality might result from a direct impact on berry metabolism or derive indirectly from the influence that light exerts on leaf and canopy function and ii) unless specific conditioning systems are provided, it is very difficult to disentangle light-induced effects from the temperature-driven ones.

In term of research focus, the 70s, 80s and 90s have tackled successfully important items related to the relationship between grape quality and light interception and distribution within the canopy (Dokoozlian and Kliewer, 1996; Smart, 1985), clarifying the role of canopy density, leaf layer number, ratio between total and “functional” vine leaf area and attempting also at defining optimal fractions of light transmitted into the fruit zone of the canopy (Mabrouk and Sinoquet, 1998). These studies contributed to the awareness that while some key must compositional traits, namely TSS, do respond to whole canopy (i.e. fruiting and vegetative zones) behavior and crop load, the fate of malic acid and many secondary metabolites seem to be especially sensitive to more local effects pertaining to the cluster zone. Such awareness associated with advances in genetics, transcriptomics and

metabolomics has led more recent research to focus on various manipulations of the fruit zone or even the single cluster light regime to assess origin, extent and consistency of variation of important berry constituents.

Many contributions have been reported about grape ripening sensitivity to shading imposed at specific stages of berry development. Dokoozlian and Kliewer (1996) pioneered this field with a phytotron study where fruit shading at selected berry growth stages was imposed vs. a fully exposed control in Cabernet sauvignon and Pinot noir indicating that, while some components such as pH and tartaric acid were insensitive to light treatments, clusters of control vines always had higher skin berry anthocyanins and phenolics than shade treatments. Though, ripening was especially delayed when light limitation occurred during stages I and II of berry growth and restoration of non-limiting light during stage III did not result in any significant recover. Results obtained by Dokoozlian and Kliewer (1996) under controlled conditions allowing good temperature handling were not always confirmed by subsequent field studies. True role played by light on anthocyanins synthesis in berries was dramatically challenged by field work on cv. Shiraz (Downey et al., 2004; Ristic et al., 2007) showing that pre-flowering dark boxing of clusters carried out until harvest did not change, in two out of three years, total anthocyanins and the expression of gene encoding UFGT. Rather, the shading impacted more the relative composition of anthocyanins increasing the ratio of di-substitute forms vs. tri-substitutes as it was also found by Koyama and Goto-Yamamoto (2008), Rustioni et al. (2011) and Guan et al. (2016) in other red cultivars. Moreover, prolonged shading reduced pro-anthocyanidins in the skins more than in seeds (Ristic et al., 2007), as it was also found by Fujita et al. (2007).

Results presented insofar instill the doubt that response to light exclusion or limitation during specific berry growth stages is strongly genotype-dependent. In cv. Nebbiolo, low and excessive light exposures led to lower anthocyanins accumulation in clusters (Chorti et al., 2010); full cluster shading imposed on cv. Norton grapevines through different canopy manipulations decreased TSS but had no effects on anthocyanins and phenolics (Jogaiah et al., 2012); conversely, excluding light from fruit-set to one week pre-veraison increased anthocyanins in the berry skins of cv. Jingxiu grapevines, whereas the same treatment applied across veraison (from one week pre- to one week post) had an opposite effect (Li et al., 2013). Similarly, in Cabernet sauvignon, while early shading did not affect anthocyanins concentration at harvest (Koyama and Goto-Yamamoto, 2008), shading applied during ripening did limit final berry pigmentation.

These results have also led to investigate if and how the genetic background can be responsible for sunlight-dependent vs. sunlight-independent anthocyanins biosynthesis in berry skin and, as a matter of fact, comparing the cvs. Jingxiu and Jingyan demonstrated that UFGT (UDP-glucose:flavonoid 3-O-glucosyltransferase) was expressed at high level in sunlight-excluded Jingyan grapes and was not in sunlight-excluded Jingxiu, and this correlated with the phenotypic coloration (Zheng et al., 2013). Moreover, Guan et al. (2016) have recently shown that light exclusion throughout berry development in Gamay (white-fleshed) and Gamay Fréaux (teinturier mutant) has reduced total anthocyanins more severely in the skin of Gamay than in the skin and flesh of Gamay Fréaux. This result suggests also a tissue-specific response.

Under no doubts, regardless of the scale of measurements, the most constant response observed in a multitude of studies is the positive relationship between light and grape flavonols, especially quercetin-3-glucoside (Cortell and Kennedy, 2006). Del-Castillo-Alonso et al. (2016a) in a study where phenolic composition was assessed in different locations from Spain to Germany covering a wide range in latitude, showed that radiation was highly correlated with flavonols and poorly linked to anthocyanins; another study conducted on Cabernet sauvignon grown in the Negev Highlands showed an exponential increase in flavonol concentration with increasing light and, interestingly,

a reduction in within cluster variability (Reshef et al., 2017). In the cv. Riesling grown in Germany, increased cluster illumination was positively correlated with content and concentration of phenolics (Friedel et al., 2015).

In terms of effects bound to variation in light quality, large interest has risen about effects due to exclusion or filtering of UV radiation. Del-Castillo-Alonso et al. (2016b) have shown a linear or exponential relationship between UV_B dose and synthesis of quercetin and kaempferol, while no effects were noted for anthocyanins, flavanols, stilbenes and cinnamates. Filtering UV_B from light hitting cv. Malbec clusters grown at high altitude had the only effect of decreasing flavonols and their anti-oxidant forms (Alonso et al., 2016) without affecting berry weight, sugar content and phenolic compounds. Similar effects were seen in the cv. Graciano, where UV_B filtering reduced miricetin-3-glucoside only (Del-Castillo-Alonso et al., 2015) and in Cabernet sauvignon (Koyama et al., 2012). In cv. Malbec, Berli et al. (2015) showed that the exposition to UV_B and the application of exogenous ABA sprays were the most effective combination at enhancing phenolics at the expense of sugar and yield. In order to identify if and how UV modulates the berry skin transcriptome, UV blocking and transmitting filters were used to modify incoming radiation in a cv. Tempranillo vineyard (Carbonell-Bejerano et al., 2014). The expression of 121 genes coding mainly for flavonol and mono-terpenoid biosynthesis was significantly altered by UV radiation. Finally, modifying the light quality spectrum in the field by supplementing from 20 days before veraison until harvest red (R, 660 nm) and blue (B, 470 nm) light resulted in a significant increase in total phenolic compounds in cv. Malbec (González et al., 2015).

Still insufficient seems to be the amount of knowledge relating light and aroma components. Different shading treatments (100 and 50% reduction) imposed at fruit set on clusters of the white cv. Grillo grown in Sicily, an area characterized by hot climate, resulted in less flavanols and pro-anthocyanidins and more flavors than the exposed berries (Scafidi et al., 2013). Dunlevy et al. (2013) investigated in cv. Cabernet sauvignon the effect of light exposure on the precursor 3-isobutyl-2-hydroxypyrazine (IBHP) and the VvOMT3 gene responsible for the final step in metoxypyrazine biosynthesis which were both drastically reduced under high light exposure. A summary of expected variation vs. increasing light of primary and secondary metabolites of the grape berry is shown in Fig. 1.

3.4. Temperature

The boost of papers published over the last 20 years about the impact of high temperature on grapevine function and berry composition has been also fostered by the global warming issue (Pallioti et al., 2014). However, some key papers in particular disclosed new perspective in terms of the differential effects that light and temperature exert on grape quality. Bergqvist et al. (2001) did a study which exploited the thermal-radiation conditions established on north and south facing row sides of EW oriented rows of cvs. Cabernet sauvignon and Grenache grown in San Joaquin Valley (California, U.S.A.), a growing area characterized by hot climate. They found that anthocyanins and phenolics increased linearly with light exposure for the N-facing side, whereas they declined when cluster exposure on the South side exceeded a PAR of 100 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Spayd et al. (2002) added consistency to the above demonstrating that when west-exposed clusters bore on NS oriented rows of Merlot grown in Yakima Valley reaching T well above 40 °C were cooled in the field to the temperature of shaded clusters, their total skin anthocyanins concentration increased in both years of the study. Notably, flavonols did not respond to the same type of conditioning. Finally, another field study on cv. Merlot (Tarara et al., 2008) where “in situ” forced convection systems were allowed to create a dynamic range of temperatures for either exposed and shaded clusters, showed that the combination of low radiation and high T was the worst for skin anthocyanins accumulation and that high T preferentially led to synthesis of acylated and di-hydroxylated forms,

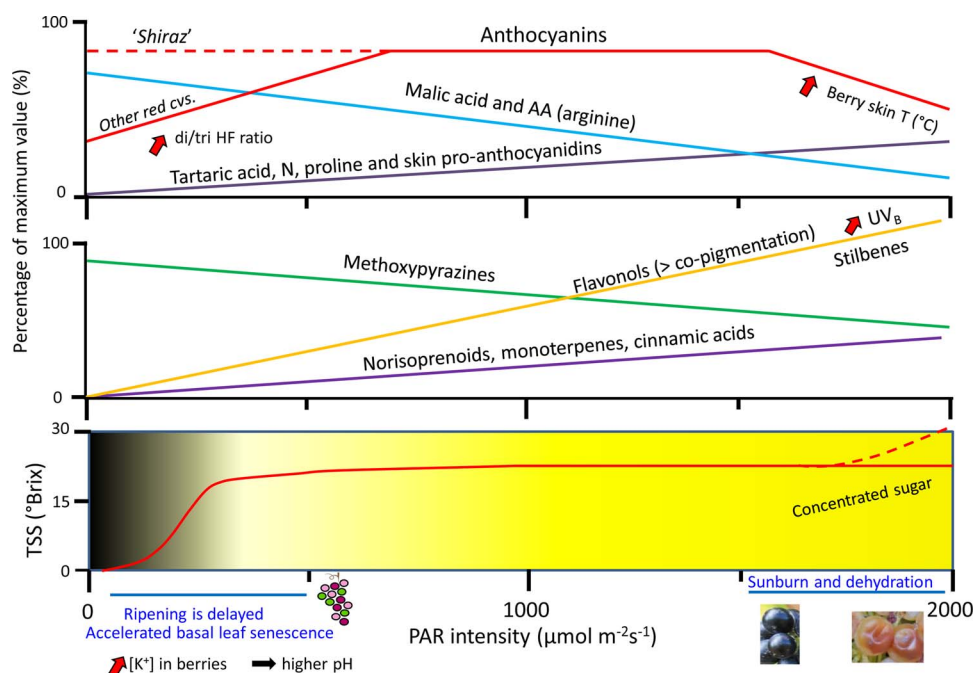


Fig. 1. General trends of variation of main grape composition parameters versus increasing photosynthetic active radiation (PAR). HF = hydroxylated forms of anthocyanins; UV, ultraviolet; P_n = net photosynthesis; TSS = total soluble solids. Trends reported in top and mid panels takes into account PAR effects on synthesis and degradation of each component. Dotted red line in bottom panel refer to anomalous late season TSS increase due to berry shrinkage. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.) Data taken from various Authors.

while confirming the scarce sensitivity to temperature of flavonols.

This set of experiments led to conclude that some fruit components (namely anthocyanins) are especially sensitive to temperature rather than light (the opposite of what it was found for flavonols) and boosted more work on genotype sensitivity and mechanisms regulating the lower color synthesis with increasing heating. De Oliveira et al. (2015) found that air T max exceeding 35 °C inhibits color formation in Grenache more than in Carignan; in the cv. Kyoho, Shinomiya et al. (2015) proved that $T > 27$ °C during the ripening season induced low color, ABA content and anthocyanin biosynthetic gene transcripts levels irrespective of the light conditions. To shed more light into the mechanism of inhibition of anthocyanin accumulation in the skin of grape berries due to high temperatures, Azuma et al. (2012) and Mori et al. (2007) showed that, in Cabernet sauvignon, the decrease in anthocyanin accumulation under high temperature (maximum 35 °C) results from factors such as anthocyanin degradation as well as inhibition of mRNA transcription of the anthocyanin biosynthetic genes.

Another interesting research field is how modifications of the diurnal temperature range (DTR) would affect grape composition. A series of experiments by Cohen et al. (2008, 2012a, 2012b) on cv. Merlot where the DTR was compressed at both pre- and post-veraison by cooling berries during the day and heating them during the night showed overall mild effects on pro-anthocyanidins, whereas berry development and the inception of veraison were hastened. DTR compression also favored the partitioning of anthocyanins and flavonols towards B-ring di-substitution. Overall, damping the diurnal T fluctuation had a marked effect on the rate of fruit development, whereas total heat summation as affected by treatments had stronger effects on phenolic metabolism alone.

More recently, a lot of attention has been put at analyzing how high temperatures can affect seasonal dynamic of berry compositional traits. Sadras et al. (2013) were first to demonstrate that elevated temperature decouples berry sensory traits, and that this effect is cultivar-dependent. In a more specific paper on cvs. Shiraz and Cabernet franc grown in Australia, Sadras and Moran (2012) tested the hypothesis that elevated temperature decouples anthocyanins and TSS in developing berries and explored the effects of fruit load and water supply on the putative decoupling. In fact, elevated temperature decoupled anthocyanins and sugars in berries by a relative shift in onset rather than rate of accumulation of these berry components and such effect was fairly

stable across crop levels and water regimes. Another study on the interaction between two cluster thermal regimes (control vs. heated) and two water deficit levels (well-watered vs. stressed) carried out in Barossa Valley on cv. Shiraz confirmed that the quite common effect of water deficit leading to colorful and flavorful wines rich in phenolic substances may not be held under high temperature (Bonada et al., 2015). Anthocyanins:sugar decoupling seems to be confirmed also by studies where no specific cluster T conditioning was devised and, rather, year-to-year variability of heat summation was exploited. On the cv. Maturana tinta grown in La Rioja (Spain), Martinez de Toda and Balda (2015) showed that both total anthocyanins and the anthocyanins:sugars ratio decreased, significantly, in the warmer area during the three years and the magnitude of such effect correlated with diurnal T recorded in the month of August. In Cannonau and Carignan, De Oliveira et al. (2015) showed that in unscreened controls elevated temperatures decreased total skin anthocyanin (TSA) and increased the degree of derivatives acylation as compared to screened vines. In Cannonau total soluble solids increases were not followed by increasing TSA as in Carignan, due to both lower phenolic potential and higher sensitivity to permanence of high temperatures. Barnaud et al. (2014) analyzed a climate gradient along a 700 km transect, covering all wine regions of Western Australia, to explore and empirically describe influences of climate on anthocyanins, pH and TA levels in red cultivars of *Vitis vinifera* (Cabernet Sauvignon and Shiraz). The results showed that, at a common maturity of 22 °Bx, berries from the warmer regions had low levels of anthocyanins and TA as well as high pH compared to berries from the cooler regions. A three-year field study collected and analyzed berry samples of Pinot noir grown in California (Nicholas et al., 2011) to establish climate statistics with main phenolic categories (anthocyanins, tannins, and total phenolics) derived from hourly temperature measures. The results from these statistical models showed that cool conditions following harvest the year before maturity, warm temperatures from budburst to bloom, and cool temperatures from bloom to veraison (the onset of ripening) were positively correlated with concentrations of all three classes of phenolics.

The patrimony of knowledge being piled up over years on the possible harmful effects that excessive temperatures and/or hot spells may induce on grape quality has also fostered research on tools and techniques available for adaptation. Whole-canopy net shading (62% transmission of incoming PAR) imposed from veraison until harvest on

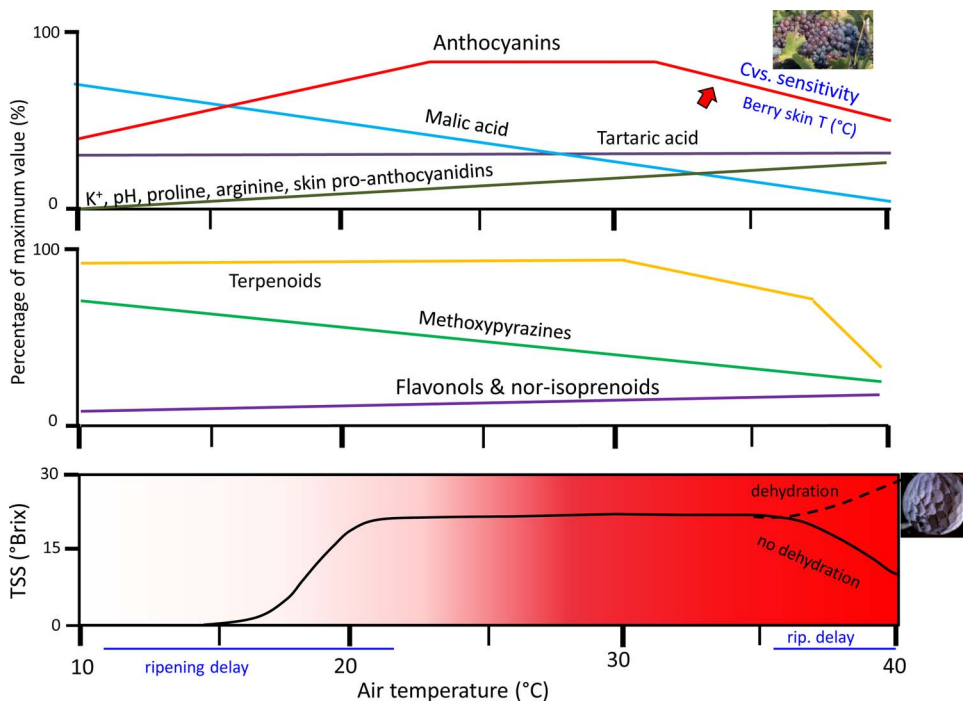


Fig. 2. General trends of variation of main grape composition parameters versus increasing air temperature (T). P_n = net photosynthesis; TSS = total soluble solids. Trends reported in top and mid panels takes into account T effects on synthesis and degradation of each component. Dotted black line in bottom panel refers to anomalous late season TSS increase due to berry shrinkage. Data taken from various Authors.

cv. Shiraz vines (Caravia et al., 2016) was effective at increasing leaf function, reducing cell death rate as well as TSS with no major changes in total anthocyanins. Paciello et al. (2017) recently tested the efficacy of an automated spraying system turned on any time air temperature went above 30 °C. The maintenance of temperature below 30 °C reduced leaf stress linked to high temperature and irradiance regimes as highlighted by the decrease of H_2O_2 content and catalase activity in the leaves. A higher amount of total polyphenols and organic acids and lower sugars characterized the grapes of cooled vines. A summary of expected variation vs. increasing temperature of primary and secondary metabolites of the grape berry is shown in Fig. 2.

3.5. Water availability

The effects that amount, timing and modalities of water supply have on grape composition are notoriously complex and have been the focus of hundreds of papers over the last decades. Complexity derives from interfering effects due to annual variable rainfall, rootstock, scion response (e.g. isohydric vs. anisohydric as outlined in Schultz, 2003) and crop load (i.e. leaf-area-to-fruit ratio). Despite such complexity, it is still possible to group the research work done insofar into three main pillars: i) papers mainly focusing on differential vine sensitivity to water stress occurring pre- vs. post-veraison (Fig. 3); ii) papers investigating the best irrigation schedule [e.g. sustained (SDI) or regulated deficit irrigation (RDI) or partial rootzone drying (PRD) as compared to rainfed or full irrigation] in order to achieve vigor control, no or moderate yield reduction and improved grape composition (Bindon et al., 2008; Shellie, 2014) and iii) a number of more recent contributions addressing the interactions between water deficit and summer pruning operations. We will more specifically focus on pillars ii and iii) in the 4.9 section of the following chapter.

Several contributions nicely summarized in Keller (2015) have confirmed that although the berry is never hydraulically isolated from the vine (i.e. the berry xylem remains functional after veraison) the sensitivity of berry water status to soil and vine water status declines greatly after veraison, when the phloem becomes the main water source for the berry. The most convincing evidence for that is provided in Lang and Thorpe (1989) where at increasing vine water stress the amplitude of berry shrinkage during the day and expansion at night linearly

follows the severity of the imposed stress pre-veraison while becoming almost insensitive post-veraison. Therefore, being other factors equivalent, the same degree of water stress is expected having an higher impact on yield and grape quality pre-veraison rather than post-veraison. A number of papers (Basile et al., 2011; Girona et al., 2009; Intrigliolo et al., 2016; Junquera et al., 2012; Merli et al., 2015, 2016; Munitz et al., 2017; Shellie and Bowen, 2014) have confirmed this although response variability within each phenological stage can be substantial. The most consistent response to pre-veraison is a yield limitation primarily driven by a reduction in berry size. Since such reduction in size is usually carried on until harvest (Ojeda et al., 2002), final smaller berries usually have higher TSS and, due to a higher incidence of skin weight over total berry weight, higher anthocyanins and phenolic concentration (Casassa et al., 2015). However, Matthews and Anderson (1988) have reported that low water status (i.e. leaf water potential allowed to become 0.3 MPa more negative than that measured on well-watered vines) imposed pre-veraison on Cabernet Franc vines grown in the North Coast Region of California determined significantly lower malic acid concentration in grapes at harvest, whereas a post-veraison stress specifically promoted proline accumulation.

When it comes to evaluating grape quality as affected by post-veraison water stress, indeed variability of related effects increases. Both anthocyanin concentration and content were largely improved in a four-year-study on Merlot under limited water supply from veraison onward (Bucchetti et al., 2011); conversely, Intrigliolo et al. (2012) warned that reducing in cv. Tempranillo water supply post-veraison can impair sugar accumulation due to detrimental effects of water stress on leaf photosynthesis. Girona et al. (2009) quantified such effect on the same cultivar and concluded that overall grape quality is increased by a late season water deficit provided leaf water potential does not drop below the -1.1 MPa threshold. Shellie and Bowen (2014) in a study on Cabernet sauvignon and Malbec were able to conclude that as long as the soil-to-leaf water potential gradient between a well watered and a water deficit treatment (23% of ET) remains above -0.75 (± 0.04 MPa), berry fresh mass and TA decrease with decreasing leaf water potential (ψ_l) whereas TSA concentration increases. Applying a pre- or a post-veraison water deficit might also affect composition of single anthocyanidins; Ollé et al. (2011) found that a post-veraison stress particularly enhanced in cv. Shiraz malvidin and p-

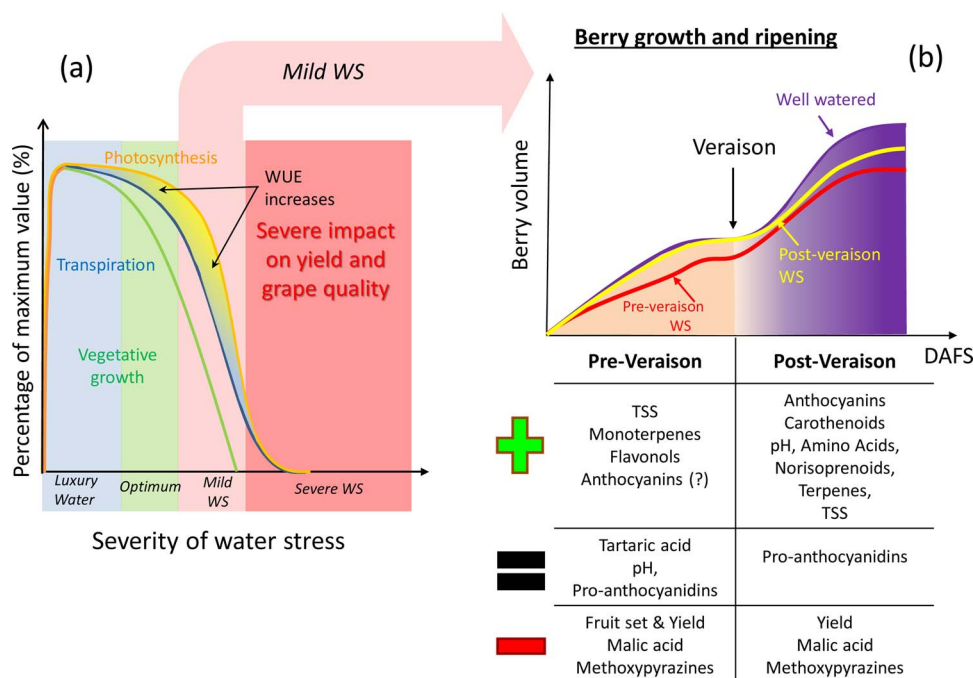


Fig. 3. Panel (a); general responses of vegetative growth and gas-exchange for an increasing water stress; panel (b): predicted changes in berry volume and several compositional parameters for a mild water stress occurring pre or post-veraison. DAFS = days after fruit set; WS = water stress; WUE = water use efficiency. Data taken from various Authors.

coumaroylated derivatives.

Being berry size the most responsive growth parameter to water deficit, a big wonder is if positive effects induced by water deficit are primarily dependent from the higher relative skin growth normally occurring in smaller berries or if more direct genetic and metabolic prompting occurs. As per the role of berry “size”, Roby et al. (2004), have shown in cv. Cabernet sauvignon that when berries sampled from high and low water status plots are segregated into six size categories to test independently for relationships due to size or water status, the effect of vine water status on the concentration of skin tannins and anthocyanins was much greater than the inherent berry size effect on the same variables. Concurrently, Castellarin et al. (2007a, 2007b) showed that, for an early or late water stress, increased TSA results from earlier and greater expression of the genes controlling flux through the anthocyanin biosynthetic pathway.

4. Agronomic factors affecting grape quality

4.1. Yield-quality relationship

Achievement of optimal grape quality is strictly linked to vine vigor and yield; therefore it is crucial to define, for each viticulture situation and type of wine, a correct balance between vegetative and productive activity. As a general rule, a balanced canopy shows a rapid shoot growth up to the fruit-set and then it slows down and stops its growth at pre-veraison to favour the ripening process. Despite such physiologically sound principles, Old World viticulture is still quite fascinated by the assumption that there is a linear decrease in quality as yield (either per vine and/or per hectare) increases. This inherently emphasizes the importance of maintaining a low number of buds per vine while pushing up the number of vines per unit of land. The New World viticulture has indeed the merit of having questioned such postulate and, while showing much more flexibility with the yield/quality relationship, also admits that very lightly pruned vines (see the case of “minimal pruning” in Australia) can lead to good or excellent quality (Clingeleffer, 1993). Bud load is an important factor affecting the yield and cluster quality of table grape cultivars and in Thompson Seedless, the reduction of bud load increased TSS and acidity (Baiano and Terracone, 2012). Furthermore, full vineyard mechanization and quality are not seen as contrasting factors and preference, when

possible, is given to short (spur) pruning (Howell, 2001).

Literature provides today enough evidence (Clingeleffer, 1993; Howell, 2001; Hunter, 1998; Poni et al., 2004) that the yield/quality relationship is adequately described by an optimum curve with initially increasing quality, followed by a plateau, and then a reduction in quality when yield is further increased. Additionally, several studies carried out on hedge or minimal pruning (Clingeleffer, 1993; Intrieri et al., 2001; Martinez de Toda and Sancha, 1999; Poni et al., 2016; Possingham, 1994) suggest that yield per vine can be increased to a certain extent without impairment for quality. Roby and Matthews (2004) showed that depending upon the causal factor leading to low yield (pruning level, cluster thinning, water stress) the style of the wines obtained from the same “low cropping” vines can vary from “more veggie and less fruity” to “more fruity and less veggie”. It is felt that the best achievement in terms of yield-quality relationship in grapes is that suitable quality can be reached within a range of crop levels provided that “vine balance” is satisfied. Such balance is effectively defined by the “leaf area-to-crop weight” ratio that for undivided canopies should vary from 0.8 to 1.2 m²/kg in order to assure adequate levels of TSS and coloration (Kliewer and Dokoozlian, 2005). In more details, 1.2 m²/kg seems to be a suitable ratio for full-bodied and structured red aged wines, whereas 0.8 m²/kg is adequate for white varieties or red varieties for the production of light wines and/or ready to drink wines. When values are below 1.0, the crop yield/pruning weight ratios are generally above 10 thus indicating over cropping (Kliewer and Dokoozlian, 2005).

The “vine balance” invoked above can be achieved through a number of canopy management practices reunited under the name of “summer pruning”. It comprises a set of practices performed on the canopy during the growing season with an array of aims, including regulation of size, vigor and crop. While it is commonly heard that the ‘perfect’ vineyard needs no summer pruning, perfect in reality has proved to be a very rare occurrence. The major change is that a given summer intervention is not solely or exclusively seen as something the grower “has to do”, say, to accommodate adjustments for excessive shoot growth or canopy density. Rather it should also be viewed as something that the grower may use to head vine and cluster growth towards better grape composition. It is not indeed a case that a few innovative summer pruning techniques have been recently tested to decelerate an overly quick and unbalanced ripening (Pallioti et al.,

2014).

4.2. Cluster thinning

While in the scientific community there is a general consensus that the time consuming cluster thinning should be left to exceptional cases of objective over-cropping, several producers prefer to interpret winter pruning as a “rough” regulator of the cropping level and use cluster thinning for the “fine tuning” of the final yield level.

Based on well-established source-sink relationships (Kliewer and Dokoozlian, 2005), it is conceivable to think that cluster thinning is necessary when a manifested situation of over-cropping does exist or when removal of part of the crop aims to induce specific compositional features in the retained clusters (i.e. high color and extract, etc.). Then, it appears to be questionable that thinning is applied even when the vine is already balanced. It is not therefore a case that the effects of cluster thinning on fruit composition and wine quality are quite contradictory; moreover, location, application time (anywhere from fruit set to veraison) and severity (from 20% to more than 50%) further contribute to variability.

Several papers (Hannam et al., 2015; Keller et al., 2005; Preszler et al., 2013) have shown that the “marginal profit” (i.e. quality improvement as a compensation for yield loss) derived from a cluster thinning is dramatically reduced and, on the other hand, the risk of undesirable side-effects (e.g. offsetting growth by the retained clusters, which might actually become more compact and also feature bigger berries with a lower skin-to-pulp ratio) increases. Conversely, cluster thinning might play an important role in all cases where over cropping occurs and there is an objective need to achieve or speed up ripening especially in cool climate areas (Bubola et al., 2011; Guidoni et al., 2002; Reynolds et al., 2007; Zhuang et al., 2014). In such studies, TSS and color largely increased in thinned vines, whereas TA was reduced and pH increased. Cluster thinning is a common practice in table grape vineyard management in order to improve fruit quality (Ferrara et al., 2016a). In Muscat Hamburg, cluster thinning done at veraison showed important effects on quality, with higher berry and cluster weight and increased phenolic compounds, total anthocyanin and volatile terpenes contents (Kok, 2016).

4.3. Leaf removal

4.3.1. Leaf removal applied around the clusters after anthesis

Leaf removal is usually identified as the operation of pulling off leaves from the basal portion of the shoots where clusters are also located. Traditionally, this intervention is carried out on dense canopies between fruit set and veraison with the aim of improving light penetration and air circulation around the clusters.

If leaf removal is conducted on truly dense canopies (more than 5 m² leaf area per m of row length according to Dokoozlian and Kliewer, 1995) its benefits are promptly shown as improved ripening (higher °Brix, color, aromas and lower titratable acidity) and lower bunch rot (Bledsoe et al., 1988; Dokoozlian and Kliewer, 1995; Haselgrove et al., 2000; Kliewer and Smart, 1989; Percival et al., 1994; Reynolds et al., 1994; Reynolds et al., 1996; Zoecklein et al., 1992). One of the most spectacular effects induced by leaf removal applied on very dense canopy is the increased biosynthesis of anthocyanins and other flavonoids (Dokoozlian and Kliewer, 1995; Haselgrove et al., 2000; Kliewer and Smart, 1989) whose biosynthetic pathway requires that a minimum threshold of light intensity (about 150–200 μmol m⁻² s⁻¹) is needed for optimum activity of key enzymes (i.e. phenylalanine ammonia lyase). Furthermore, if the leaf removal is undertaken on dense canopies the amount of photosynthesis lost for having stripped the leaves can be at least partially compensated by the re-exposure to light of the underlying leaf layers. Under this connection, it is a general thought that basal leaf removal carried out at veraison has a minor influence on the total canopy photosynthesis budget since older,

already senescing leaves are pulled out. This assumption is not necessarily true since the bigger size of the basal leaves can compensate for their lower photosynthetic capacity so that the contribution of the basal shoot zone can be similar to that of the above-located shoot portions. This finding can in part explain why leaf removal has less consistent effects on grape quality when it is applied on already balanced vines or involves the complete removal of all basal leaves including laterals. Excessive leaf removal may in fact be detrimental for white wines (drop of malic acid due to overheating of the cluster zone) and also for reds (inhibited anthocyanins biosynthesis due to excessive berry temperatures paralleled by a concurrent increase of the flavonol quercetin) (Haselgrove et al., 2000; Price et al., 1995; Reynolds et al., 1994). Ongoing research has provided knowledge to distinguish two more types of leaf removal aimed at quite distinct goals:

4.3.2. Pre-flowering leaf removal

This practice has mainly been inspired from long-standing knowledge according to which carbohydrate supply at flowering is a primary determinant of fruit set (Coombe, 1992). The temporary source limitation induced by removing about 6–7 main basal leaves before flowering has led, under a broad array of genotypes and growing conditions, to a significant decrease in fruit-set, which in turn increases cluster looseness and tolerance to rot (Diago et al., 2010; Komm and Moyer, 2015; Moreno et al., 2015; Poni et al., 2006). Yet, irrespective of genotype, this technique markedly improves grape composition (TSS, anthocyanins, phenols and aromatic compounds) and wine sensory properties as compared to non-defoliated vines (Diago et al., 2010; Palliotti et al., 2011; Poni et al., 2006; Sivilotti et al., 2016). Poni et al. (2008) have shown that main reason for quality improvement is because in early defoliated vines seasonal carbon supply per unit of crop can increase up to 38% compared to C vines as a combined result of lower yield, lower canopy age and photosynthesis compensation. The technique can be easily mechanized (Intrieri et al., 2008) and its effects also reproduced using anti-transpirant compounds (Palliotti et al., 2010).

4.3.3. Late, apical to the cluster leaf removal

Post-veraison apical to the cluster mechanical leaf removal is a brand new technique effective at delaying TSS accumulation in the berry without hindering phenolics. Its physiological background is that, around veraison, leaves located on the apical two-third of the canopy are the most functional having reached full expansion while still being far from senescence (Poni et al., 1994). A two year study (2011–2012) on mechanical post-veraison, apical to the bunch zone, leaf removal on cv. Sangiovese has evinced a reduced leaf-to-fruit ratio (from 1.77 to 1.13 m²/kg) and demonstrated its potential to delay optimal TSS accumulation in the berry by about 2 weeks as compared to non-defoliated vines (Palliotti et al., 2013). At the same harvest date, defoliated vines had 1.2 lower °Brix in the must and such difference carried onto the wine alcohol contents (–0.6% vol.). Similar results have been obtained also on cv. Montepulciano by Lanari et al. (2013), whereas Poni et al., 2013 on cv. Barbera have confirmed a delay of technological ripeness without affecting color and phenolics. It is advised to perform apical leaf removal at around 12–14 °Bx ensuring that at least 30–35% of the leaf area is removed. This canopy management technique is very attractive as it is easily mechanized and the fact that canopy area targeted for leaf removal is spatially distant from the fruiting area, while inherently solving the problem of cluster damage, allows a machine speed which is higher than traditional mechanical leaf removal insisting on the basal portion of the canopy.

4.4. Shoot trimming

Shoot trimming is a common and mechanisable practice used to maintain canopy shape, contain vine vigor, increase the efficiency of disease treatments and facilitate harvest and access of machines to the

vineyard rows. The effects of shoot trimming on grape quality are closely associated to the amount of the leaves retained on the stem after cut and to amount and efficiency of lateral shoots triggered by trimming (Keller et al., 1999; Poni and Giachino, 2000), which, in turn, are a function of timing and severity. Severe hedging, i.e. less than six-eight main leaves retained per shoot, generally reduces grape quality especially when applied late in the season with little chance to get adequate lateral regrowth, whereas effects due to timing of application is rather controversial (Kliewer and Bledsoe, 1987; Reynolds and Wardle, 1989).

VSP trellises are normally trimmed when their shoots exceed the top wires. Therefore, the timing is poorly dependent on grower's decisions and it is instead a function of intrinsic shoot vigor and vine balance. A balanced vineyard would reach the height suitable for trimming around fruit set, whereas an excessively vigorous one would get to the same growth stage much earlier, therefore making shoot trimming more likely to be repeated again later in the season. Timing of trimming follows different rules when performed on sprawl canopies (i.e. a single high wire trellis) where a pre-flowering shoot trimming might become necessary to induce mostly upright shoot growth (Poni et al., 2014). In different red and white grapevine cultivars grown on fertile soil and trained to a single high wire trellis, the hedging at the 9–10th node on primary shoots, carried out one week after bloom, increased the contents of TSS, phenols and anthocyanins in the red cultivars and reduced the TA and juice pH in all the cultivars (Cartechini et al., 2000). Late-hedging, five weeks after bloom, instead reduced yield and TSS content as well as anthocyanins content in red cultivars.

More recently, quite targeted applications of shoot trimming have proven successful. Bondada et al. (2016) have shown that post-veraison shoot trimming can be valuable at reducing cluster compactness without compromising overall fruit quality in Sangiovese. In the same cv., Filippetti et al. (2015) have shown that a late season severe trimming (8 main leaves retained at 12 °Bx) is effective at delaying sugaring without impairing anthocyanins and seed tannins. Postponing first shoot topping to the latest technically possible moment (i.e. 4 weeks after the end of flowering) in cvs Pinot gris and Riesling grown in a cool climate also achieved improved cluster architecture leading in turn to much delayed bunch rot epidemic (Molitor et al., 2015) but, differently from the work done by Filippetti in a warm climate, it also strongly enhanced ripening (0.77–2.24 °Bx more than the standard treatment). In cvs. Grenache and Tempranillo grown in Spain, a severe shoot trimming performed at pea-size significantly reduced the leaf area-to-yield ratio as compared to untrimmed and the resulting delay in ripening (20 days) was beneficial for getting higher anthocyanins at the same sugar level (Martinez De Toda et al., 2014).

4.5. Shoot thinning

The aim of this management practice is to assure an optimal canopy density and/or crop level and it is usually done when the shoot length is between 15 and 25 cm. Improved canopy microclimate and physiology can be achieved within shoot density of 15–25 shoots/m of row (Smart, 1985). Usually, shoot thinning reduces vine yield and titratable acidity, whereas improves TSS, anthocyanins, aromatic compounds and tolerance to rot (Bernizzoni et al., 2011; Reynolds et al., 2005). In cv. Barbera, Bernizzoni et al. (2011) have shown that when thinning reduced shoot density from 30 to 15 units per meter, in about two weeks whole-canopy photosynthesis of the thinned vines approximated that of unthinned plants.

4.6. Trunk (cane) girdling and application of PGRs (plant growth regulators)

Girdling (removing a ring of bark) of the trunk or cane may be performed right after fruit set to increase berry size and also at the beginning of fruit ripening or berry softening to improve fruit color and advance fruit maturation (Dokoozlian et al., 1995; Ferrara et al.,

2014a). The interruption of phloem vessels is temporary (several days) and the vine then restores the vessels through the production of a callus. This practice is more often used in table grape seedless varieties to improve the size (Dokoozlian et al., 1995). Gibberellic acid (GA₃) has been used extensively to control berry size, set and weight, to decrease cluster compactness and to induce the absence of seeds in grapes (Mullins et al., 1992). Application of GA₃ at different concentrations to seedless table grape cultivars is a common practice for elongating the bunch, thinning flowers, and increasing berry size. GA₃ can be applied at different phenological stages depending on the final goal: 1) pre-flowering, to elongate the rachis; 2) during flowering, for thinning flowers of seedless grapes; 3) post-flowering and fruit-set, to increase the berry size (Dokoozlian, 2000). In recent years, there has been a significant use of PGRs to increase berry size and consequent yield. Cytokinins are particularly used for berry enlargement and often applied with gibberellins to stimulate cell division and elongation and the most common cytokinin used in viticulture is forchlorfenuron, with the trade name of CPPU (Ferrara et al., 2014a). Exogenous ABA application is used in the production of table grapes to hasten ripening and increase berry color of different colored varieties (Cantín et al., 2007; Ferrara et al., 2013, 2015; Peppi et al., 2006). S-ABA effects on color in Crimson Seedless are the consequence of changes of both the concentration of total anthocyanins and the ratio among different types of anthocyanins (Ferrara et al., 2015). Also the application of an ethylene-releasing compound, 2-chloroethylphosphonic acid, stimulated the accumulation of anthocyanins and advanced ripening (Dokoozlian et al., 1995). Methyl jasmonate, 1-aminocyclopropane-1-carboxylic acid (ACC), coronatine, ethephon, stimulated the abscission of mature grape berries of raisin, table (ready-to-eat fruit) and wine grapes (Ferrara et al., 2016b; Fidelibus et al., 2007; Uzquiza et al., 2014).

4.7. Training systems and plastic covers (table grapes)

The use of a suitable training system allows a better exposure of clusters and canopy to solar radiation and air circulation with qualitative improvements of the berries. The appropriate training system (tendone, parral, ypsilon, etc.) can significantly affect many cultural operations with positive effects on table grape quality (García De Cortázar et al., 2005; Ferrara et al., 2016a). Training systems require different leaf area/crop weight ratios for optimal level of total soluble solids, berry weight, and berry coloration at harvest, ranging from 0.8–1.2 m²/kg for the single canopy systems to 0.5–0.8 m²/kg for horizontally divided-canopy systems (GDC, lyre, wye) (Kliewer and Dokoozlian, 2005).

In some areas of table grape cultivation (Southern Italy), plastic covers are used as nets for hail protection or plastic sheets to advance the ripening (early harvest) or delay harvesting (late harvest) protecting the clusters from the autumn rain (Ferrara et al., 2016a). This long permanence of table grapes on the vine also allows to maintain a fully hydrated and green stalk (fresh appearance) much appreciated by consumers. Too late harvest (or long storage) may affect the quality of the grape causing berry shattering and loosening and reduction of firmness.

4.8. Fertilization and soil management (table grapes)

Pre-veraison calcium applications significantly affected fruit mechanical characteristics as shown by higher values of flesh firmness and berry breaking force and lower *B. cinerea* rots during storage thus maintaining postharvest fruit quality (Ciccarese et al., 2013). Calcium applications during the first stages of fruit development induce an increase of the final berry size (Alcaraz-Lopez et al., 2005).

Recent application of cover crops in table grape vineyards reduced the vine vigor with positive effects on yield and berry quality (Ferrara et al., 2014b; Muscas et al., 2017). In particular, the application of soil sensors showed that at 25 cm depth the average time it takes the

volumetric water content to reach the initial value before irrigation was 21% higher in the vineyard with *Trifolium repens* compared to the tilled one (Torres et al., 2017). As a consequence, the irrigation volume was $1296.52 \text{ m}^3 \text{ ha}^{-1}$ (*Trifolium repense*) and $1448.66 \text{ m}^3 \text{ ha}^{-1}$ (bare soil) with similar yields (Torres et al., 2017).

4.9. Water supply

The number of contributions comparing the effect of different DI strategies (sustained, regulated or PRD) on vine performance has probably decreased over the last years. In a trial carried out in Portugal, Santos et al. (2005) showed in cv. Castêlão that, being the amount of water supplied to each vine the same, PRD is more effective than SDI at reducing vegetative growth with better canopy opening. This resulted in a cluster microclimate conducive to higher anthocyanins and phenolics concentration in the berry skin, while TSS and pH were not affected. Comparing SDI, RDI and non-irrigated (NI) in cv. Tempranillo, Zarrouk et al. (2012) found that the main compounds affected by water availability were pro-anthocyanidins and flavonols, which increased with irrigation at any phenological stage. SDI and RDI had the highest STA at harvest and, interestingly, sugar concentration still did not differ among treatments.

More recently, attention has been devoted to interaction studies between vine water supply and cultural practices. Source limitation imposed by either water deficit and shortening of canopy wall (through trimming or reduction in the number of catch wires) showed scant interactions between the two factors (Herrera et al., 2015; Mirás-Avalos et al., 2017), although the former study carried out on cv. Merlot showed that while a pre-veraison water deficit induced higher TSS and color at harvest, early severe canopy reduction did limit sugar accumulation without impairing phenolic ripening. On the same cultivar, Cook et al. (2015) looked at the interaction of timing of mechanical leaf removal and SDI or RDI vs. yield and grape composition. Quite interestingly, pre-bloom leaf removal when combined with RDI optimized TSA. The cost to produce one unit of TSA was reduced 35% by combining pre-bloom leaf removal and RDI when compared to no leaf removal and SDI. Another study providing further evidence for mild water deficit x crop load interactions on grape composition of Cabernet sauvignon is the one by Keller et al. (2008) who adjusted crop level by cluster thinning. Zarrouk et al. (2016) investigated the water deficit x temperature interaction looking at how SDI – 30% ET and RDI – 15% ET impact on composition of clusters located on the E and W facing sides of NS oriented rows. The most severe stress condition exacerbated the negative impact of water stress on anthocyanins and the RDI-W combination had the worst behavior in terms of repression of biosynthesis at the onset of ripening and as degradation at later stages.

A new frontier in terms of precision irrigation is at glance. McClymont et al. (2012) compared uniform irrigation management vs. Normalized Difference Vegetation Index (NDVI) – derived site specific irrigation in cv. Shiraz and found that pH and titratable acidity showed increased similarity between different vigor zones, whereas other parameters were overall unaffected. Some of the effects of water deficit on grape composition discussed in the previous paragraphs are summarized in Fig. 3.

5. New methodologies for assessing grape quality

Traditional monitoring of grape quality is based on the measurement of chemical and technological parameters (even in combination) mainly represented by TSS, reducing sugars, pH, TA, visual inspection, fruit tasting and all this information is aimed mainly at optimizing the harvest timing (Cozzolino and Damberg, 2010). The International Organization of Vine and Wine (OIV) assembles all the analytical methods and protocols for grape and wine evaluation in a compendium book (OIV, 2016). These methodologies, even accurate and robust, are by now considered as limiting in terms of costs, time needed,

destructiveness and low environmental-friendliness because of the chemical reagents used.

More recently, large interest was raised by modern technologies able to overcome the limitations of traditional analytical methods, at the same time assuring high robustness and precision in the response (Dos Santos et al., 2017). Most of these new methods can be referred to non-destructive technologies, where measurements are based on the physical-chemical properties of the employed sensors (e.g. light energy, irradiance, fluorescence, optic, acoustic, etc., ...) and their interaction with the vegetal tissues. Chemometry is the multivariate statistical approach which allows to combine non-destructive information with destructive attributes (chemicals) of grapes with the goal of developing predictive models able to measure chemical parameters in intact and unknown samples (Cozzolino et al., 2006).

Sensors performing non-destructive measurements can be divided on the basis of their method of application in remote and proximal, depending if detections are carried out by distance (aircrafts, UAVs, drones) or by contact, mainly operated through ground vehicles (tractors or robots) or directly by the human action (hand-held devices) (Mateo and Di Gennaro, 2015).

Vibrational spectroscopy based methodologies have been largely studied and evaluated because of several advantages represented by their non-destructive mode and user-friendliness, the need for minimal or no sample preparation and ability to detect several quality attributes from a single measurement in a very short time of detection (Damberg et al., 2015). Two main techniques are recognized as applications of molecular vibrational motions: infrared spectroscopy (near, mid or far on the basis of the infrared spectral region involved) and Raman spectroscopy (Dos Santos et al., 2017). Infrared spectroscopy (IR) relies on the interpretation of molecular bond vibrations, in the spectral ranges between $14,000\text{--}4000 \text{ cm}^{-1}$ (near infrared, NIR region), $4000\text{--}400 \text{ cm}^{-1}$ (mid infrared, MIR region), and $400\text{--}10 \text{ cm}^{-1}$ (far infrared or Terahertz region).

Several authors have reported NIRs application aimed to measure, on homogenized grape samples and grape juices or musts, compositional parameters and maturity indicators, such as TSS, anthocyanins, ions, dry matter, condensed tannins, reducing sugars, electric conductivity, pH, and volatile compounds (Bellincontro et al., 2011; Cozzolino and Damberg, 2010; Damberg et al., 2015; Schmidtke et al., 2012). Overall, results suggest that NIR spectroscopy is a quite performing technique if aimed at predicting reducing sugar content and TSS in grape homogenates and musts (Gonzalez-Caballero et al., 2010). Damberg et al. (2015) suggested that the determination of other parameters can be strongly affected by the sample presentation mode and the low concentration of investigated compounds, such as volatiles and other secondary metabolites. Technological improvements in this scientific area allowed the spectral scanning of grape samples in different presentation modes, such as intact grape berries and whole grape bunches, both in the laboratory and in-field (Muganu et al., 2013). Interesting results, in terms of calibration and prediction as well, were obtained using a portable NIR-AOTF, a special configuration of a NIR device employing an acoustic-optical tunable filtering of the spectra wavelengths, for the monitoring of ripening evolution in intact grape berries. Regression models developed to be used as tools of analytical prediction were built by coupling spectra to reference data obtained from MIR spectroscopy (Barnaba et al., 2014). Nowadays, the most widespread commercial equipment used at a laboratory level for grape for grape musts analysis at laboratory level (WineScan, FOSS, Hillerød, Denmark) is based on MIR spectroscopy, Fourier transformed (FT) technique, and chemometric modeling (Patz et al., 2004). The device is able to detect, simultaneously and through a rapid and non-destructive method, a large number of grape parameters with a great accuracy and robustness. Giovenzana et al. (2013) successfully tested a Vis/NIR device to predict ripening parameters (TSS, TA, potential alcoholic degree and extractable anthocyanins) in both red and white grape samples directly in the field.

NIR hyperspectral imaging, a technique which provides the spatial information along with the spectral response for each pixel of the object scanned (Lorente et al., 2012) also provides interesting information concerning quality and maturity indicators in intact grapes, and it can be considered a non-destructive technique especially suited to precision agriculture applications (Álvarez-Cid et al., 2015). Recently, this technique has been successfully applied for the rapid and non-invasive evaluation of anthocyanins, TSS, pH and sugar content (Fernandes et al., 2015) and to assess grape aromatic ripening, by combining non-destructive detections and volatile compounds measurements (Álvarez-Cid et al., 2015).

All the developed methods based on vibrational spectroscopy technologies present significant advantages mainly represented by the non-destructiveness and rapidity of the detections, cost reduction in recurring usage, and the environment-friendly character of the analytical procedures. However, there are still some limitations that can reduce the effectiveness of their real employment represented as possible loss of spectral efficiency (especially for field applications), difficulty for obtaining robust and reliable calibration models due to the large number of samples required and the high biological variability of the grape samples due to their different varieties and/or origins. These limitations also can affect the relatively high cost of commercially available instruments.

A method known as chlorophyll fluorescence screening, which is based on the comparison of the chlorophyll fluorescence emission after being excited at two different wavelengths, has been tested and developed, and it enabled the indirect measurement of grape phenolic content (Agati et al., 2007; Cerovic et al., 2008). A portable fluorescence sensor has been developed and tested as an efficient tool for determining the phenolic content in different grapevine varieties in the vineyard (Ghozlen et al., 2010). The same device has also been manually used for mapping grape quality properties (Baluja et al., 2012) in the field and determining the anthocyanin content in grapes upon their arrival at the winery (Le Moigne et al., 2010). In Australia, this fluorescence sensor has been mounted on a commercial harvester and used for on-the-go measuring of anthocyanin content in red grapes destined to wine production (Bramley et al., 2011).

6. Conclusions and perspective

Multidisciplinary advancement in grapevine genetics, biotechnology, physiology and innovative cultural practices is offering today a great deal of tools suitable to achieve the desired quality at remunerative yield levels and controlled production costs. Indeed, quality can be more easily achieved growing “the right cultivar in the right place”; though is it likewise known that advantages derived from using the best *terroir* can be spoiled by improper or poor cultural practices and canopy management. Among the major advancements in managing grape quality, interactions between canopy microclimate and grape composition from one side and a sort of re-interpretation of some canopy management practices to solve or address specific issues have played a role. A great amount of knowledge is therefore available and if the right physiological principles and technique are applied according to specific need of each cultivated site, “quality” is at hand.

Perspectives are primarily for new scions and rootstocks suitable to better adapt to the changing climate as well as for better exploitation of existent biodiversity. Then, a more applied use of genomics seems wishful; for instance transcriptomic and metabolomic are precious tools to assess if and how grape quality of a given cultivar can be maintained when the same is tested at long distances from the environment of origin. Likewise, patterns of up and down regulation of genes can pave the way to preliminarily assess how stable and repeatable are the effects of a given agronomic practice under an array of environments and genotypes. Finally, grape quality will be highly impacted by the storm of precision viticulture. Once significant intra-vineyard variability is assessed, the outlook of bringing heterogeneous grape quality towards

the desired quality through, for instance, a variable rate approach, is luring.

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